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Technology to Reduce Petroleum Energy
Use in Civil Works

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Vegetable Oil Derived Fuels for Civil Works Diesel Engine Applications

by
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This report describes the final phase of research into ways of using renewable vegetable oil products as fuel alternatives for modern diesel engines supporting Civil Works. A survey of the literature revealed that vegetable oil in its neat form has three major deficiencies with respect to use as a fuel: nozzle coking, combustion chamber fouling, and excessive lubricating oil dilution. By modifying the vegetable oil through a transesterification process, a product known as methyl ester soyate (MESO) can be produced which significantly alleviates the nozzle coking and combustion chamber fouling difficulties, while decreasing lubricating oil dilution.

Laboratory experiments were conducted to study dilution and lubricating oil degradation. The conclusion was that, for dilutions of 5 percent or less, diesel engines can be operated on MESO, provided that lubricating oil condition is monitored properly. Finally, a field test of MESO in a diesel generator set is described.

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FOREWORD

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VEGETABLE OIL DERIVED FUELS FOR CIVIL WORKS DIESEL ENGINE APPLICATIONS

1 INTRODUCTION

Background

The world petroleum market is characterized by cyclical swings in supply, price, and quality. Both the Army Energy Plan¹ and the Corps of Engineers Energy Program² mandate reduced reliance on petroleum energy and increased use of alternative fuels where practical. The identification and testing of potential alternative fuels for Civil Works power requirements are important for both economic and strategic reasons.

Sliwinski and Corcoran³ previously identified alcohols, water/oil emulsions, coal, synthetic fuels (synfuels) from shale and tar sands, vegetable oils, and mixtures thereof as promising subjects for further research. This report discusses the results of laboratory and field experiments with vegetable oil derived fuels as possible alternatives for running diesel engines that support the Civil Works mission. The experiments were conducted by the U.S. Army Construction Engineering Research Laboratory (USA-CERL).

Objective

The objectives of this work were to examine the feasibility of using vegetable oil fuels in Civil Works diesel engines; identify necessary precautions and modifications during operation with these fuels; and conduct laboratory and field trials of a vegetable oil fuel.

Approach

The literature was reviewed for the most current information on combustion of vegetable oil (VO) fuels in diesel engines. Based on the findings, methyl ester soyate (MESO), a vegetable oil monoester, was tested in laboratory experiments to reproduce reported results and identify chemical interaction with engine lubricating oils. Finally, a field test was conducted with MESO using an emergency diesel generator to validate engine performance.

¹Army Energy Plan (Headquarters, Department of the Army [HQDA], 25 February 1985).

²Engineer Regulation 11-1-10, *Corps of Engineers Energy Program* (Headquarters, U.S. Army Corps of Engineers, 15 April 1982).

³B. J. Sliwinski and E. Corcoran, *Diesel Fuel Alternatives for Civil Works Prime Movers*, Interim Report E-200/ADA149738 (U.S. Army Construction Engineering Research Laboratory [USA-CERL], September 1984).

Scope

Several different methods of using VO fuels in diesel engines are examined. Mixtures and treatments include pure vegetable oil, blends of petroleum-based diesel fuel with vegetable oil, and chemically modified fuel (MESO). Data and results are primarily from high-speed, direct-injection diesel engines since this is expected to be the most sensitive application; medium- or low-speed engines would experience proportionally fewer difficulties.

Mode of Technology Transfer

This information will be transferred to the field through an Engineer Technical Letter.

2 COMBUSTION OF VEGETABLE OILS

Overview

Ever since Dr. Rudolph Diesel powered an engine with peanut oil at the Paris Exposition in 1900, compression ignition (CI) engines have been tested with many different "bio" or VO fuels. In 1980, the Illinois Department of Agricultural Engineering conducted a study on VO fuels, identifying 11 vegetable oil crops that have been or are currently being produced in the United States. These oils include: castor, corn, cottonseed, crambe, linseed, peanut, canola (low-erucic rapeseed), safflower, sesame, soybean, and sunflower.⁴ Extensive research has been done to determine which vegetable oil behaves most similarly to diesel fuel and what modifications, if any, are necessary for it to burn successfully in a conventional diesel engine.

Reviews of engine performance have had mixed results. Pure vegetable oil burns best in either large, slow-speed diesel engines or in higher speed indirect injection engines. As will be discussed in detail later, the higher viscosities and complex chemical interactions encountered when vegetable oils are burned cause a variety of problems in engines designed to burn relatively clean, distillate fuels. This chapter discusses what difficulties commonly occur, painting a less than optimistic picture for the use of VO fuels. It should be remembered, however, that the primary thrust of current research is how to burn VO in modern diesels. These engines are the endproduct of nearly a century of research and development aimed toward developing maximum efficiency and power from petroleum distillate fuels. If the world ran out of petroleum tomorrow, the marketing of diesel engines capable of burning vegetable oil could follow in relatively short order. It is only the large capital investment in an installed base of fuel-efficient, reliable diesel engines that forces the Army to consider ways of making these existing engines burn a fuel for which they were not designed.

Forgiel and Varde⁵ tested No. 2 diesel fuel, 100 percent hydrogenated soybean oil, and 100 percent peanut oil in a direct-injection diesel engine. They evaluated the engine's performance when using these three fuels and monitored changes in performance when three different injection nozzles were used. A similar study was conducted by Fishinger, et al.⁶ to determine engine durability and fuel-engine compatibility when a VO/diesel fuel blend was burned in a diesel school bus. Sliwinski and Corcoran⁷ discussed the specifics of both tests and their conclusions.

⁴C. E. Goering and M. J. Daugherty, "Energy Accounting for Eleven Vegetable Oil Fuels," *Transactions of the American Society of Agricultural Engineers (ASAE)*, Vol 25, No. 5 (1982), pp 1209-1215.

⁵R. Forgiel and K. S. Varde, "Experimental Investigation of Vegetable Oils Utilization in a Direct Injection Diesel Engine," *Alternate Fuels for Diesel Engines*, SP-503 (Society of Automotive Engineers [SAE], 1981), pp 59-66.

⁶M. K. Fishinger, et al., "Service Trial of Waste Vegetable Oil as a Diesel Fuel Supplement," *Alternate Fuels for Diesel Engines*, SP-503 (SAE, October 1981).

⁷B. J. Sliwinski and E. Corcoran.

Ryan, et al.⁸ classified the problems encountered during engine tests into two types: operational and durability. The operational problems relate to starting ability, ignition combustion, and performance; the durability problems include deposit formation, carbonization of the injector tip, ring sticking, and lube oil dilution or degradation.

To determine what causes these problems, Ryan conducted an extensive investigation. The specific objectives of the test were to determine if:

1. Improper injection and atomization characteristics, caused by the high viscosity of the oil, contribute to the engine durability problems.

2. Engine problems would be minimized if an indirect-injection (IDI) engine were used as opposed to a direct-injection (DI) engine.

The investigation consisted of burning four different vegetable oils, each in at least three different stages of processing. Their performance and combustion characteristics were monitored in both DI and IDI diesel engines.

The engines used were a Caterpillar 3306 PC (Pre-Chamber)/TC (Turbocharged) and a 3306 DI (Direct-Injection)/TC. Both engines were operated over a speed load matrix consisting of eight test points: four loads (100, 75, 50, and 25 percent of rated) each at two engine speeds. The "intermediate speed" was 1500 RPM for both engines, corresponding to the speed for peak torque; rated speed was 2200 RPM for the IDI engine and 2000 RPM for the DI engine.

After each oil was tested, the injection nozzle for the number one cylinder was removed and examined for deposits. A lubricating oil sample was also removed and analyzed for contamination by the vegetable oils. The nozzles from the DI engine displayed varying tendencies for coking, with the light hydrotreated soybean oil displaying the least and the crude oils of sunflower, soybean, and cottonseed all showing very strong coking tendencies. All nozzles from the IDI engine were similar to those removed from engines that had been run on No. 2 diesel in that no apparent tendency was found for nozzle coking. Lubricating oil contamination did not appear to be appreciable in the IDI engine.

It was concluded, within the range of fuels tested, that the IDI engine did not appear sensitive to the chemical composition of vegetable oils in terms of the durability problems that were encountered in direct-injection engines. For fuel economy, however, most modern manufacturers use direct injection in their engines.

Nozzle Coking

A major obstacle to using neat vegetable oils as a petroleum fuel substitute is the phenomenon of injector nozzle coking. In general, nozzle coking is accompanied by deposition of combustion products on cylinder walls, leading to ring sticking and contamination of engine lubricating oil. Characteristic symptoms of nozzle coking include increased engine noise and emissions along with decreased power output. It is important, therefore, to understand the mechanisms by which nozzle coking occurs and to identify the nature of the deposits.

⁸T. W. Ryan, L. G. Dodge, and T. J. Callahan, "The Effects of Vegetable Oil Properties on Injection and Combustion in Two Different Diesel Engines," *Journal of the American Oil Chemists' Society (JAOCs)*, Vol 61, No. 10 (October 1983), pp 1610-1619.

Bacon, et al.⁹ presented a detailed chemical analysis of the process of nozzle coking. The theory proposed was that the mechanism by which deposits form is through polymerization of triglyceride molecules (fatty acids) in the vegetable oils. These polymers are then partially burnt (pyrolyzed) under the combustion conditions present in the cylinder, which can lead to blockage of some or all of the nozzle orifices. The resulting degradation in fuel spray atomization and combustion efficiency can cause additional medium-term mechanical problems such as piston ring sticking and gelation of the lubricating oil.

Baranescu and Lusco¹⁰ further investigated nozzle coking through extensive tests using an alkaline refined sunflower oil in blends with No. 2 diesel fuel as well as in the neat form. Three blends were obtained by mixing sunflower oil and diesel fuel in the following proportions by volume:

- 25 percent sunflower oil to 75 percent diesel oil
- 50 percent sunflower oil to 50 percent diesel oil
- 75 percent sunflower oil to 25 percent diesel oil.

The engine used in these tests was an International Harvester DT-436B DI, turbocharged, six-cylinder model.

After each set of tests with a particular blend, the fuel injection nozzles were removed, inspected, and cleaned prior to reinstalling them in the engine. As a general trend, it was found that the deposits increased with increasing vegetable oil percentage in the fuel blend and were harder than those formed with diesel fuels. There were, however, no apparent changes in the engine performance or fuel spray pattern. Photographs taken under magnification revealed that the deposits formed craters (funnel-like structures) around the nozzle orifices but left the orifices unobstructed.

The test engine was run in a 1-hr test at low idle with a 50/50 blend of sunflower oil and No. 2 diesel oil. The nozzles were inspected and it was found that, while there were no deposits around the orifices, the nozzles were wet and oily. This finding led to speculation that a combination of high nozzle tip temperatures (characteristic of high load regimes) and poor injection cut-off and fuel dribble (characteristic of low load regimes) is likely to encourage the build-up of deposits.

The injector coking found when even partial blends of vegetable oil are burned represents a serious barrier to the use of neat vegetable oils in any form. The experiments discussed above indicated that the fouling was exacerbated by both the high viscosity of the vegetable oil and the high degree of unsaturation. Much of modern research concerning VO fuels has centered around an effort to reduce the viscosity and/or the degree of unsaturation.

⁹D. M. Bacon, F. Brear, I. D. Moncrieff, and K. C. Walker, "The Use of Vegetable Oils in Straight and Modified Form as Diesel Engine Fuels," *Beyond the Energy Crisis*, Vol 3, Third International Conference on Energy Use Management, West Berlin, October 26-30, Pergamon Press (1981), pp 1525-1533.

¹⁰R. A. Baranescu and J. J. Lusco, "Performance Durability and Low Temperature Evaluation of Sunflower Oil as a Diesel Fuel Extender," *Vegetable Oil Fuels*, Proceedings of the International Conference on Plant and Vegetable Oil as Fuels, Fargo, ND (ASAE, 1982), pp 312-328.

Combustion Chamber Fouling

Combustion chamber fouling is another obstacle that must be overcome before the long-term use of vegetable oils as fuels can be considered practical. In the experiment discussed above, Baranescu and Lusco attributed many of the problems in the combustion chamber to high viscosity of the vegetable oil. It is believed that the fuel spray plume from the injector orifices is unable to atomize completely prior to contacting the cylinder walls. They attempted to correct this condition by obtaining a blend of fuel that would meet acceptable standards for diesel fuel. The industry standard¹¹ for diesel fuel specifies that the kinematic viscosity of No. 2D diesel fuel must fall within the range of 1.9 to 4.1 (cSt) at 40 °C. Although this requirement was not satisfied by any of the fuel blends used, it was determined that a mixture of 20 percent sunflower oil and 80 percent diesel fuel would meet the requirement.

This 20:80 mixture represents the maximum blend ratio for sunflower oil to diesel fuel at 40 °C, a common injector pump inlet temperature. An increase in temperature will lower the viscosity of a given blend appreciably. At 100 °C, blends with up to 60 percent sunflower oil yielded viscosity measurements that met the specification limits, suggesting that preheating of fuel oil might be a viable method of maintaining satisfactory viscosities.

Longer ignition delays experienced in these tests can be attributed to lower cetane numbers associated with sunflower oil and its blends (cetane number is a measure of a fuel's auto-ignition ability). Under a given set of engine conditions, a fuel with a lower cetane number will require a longer ignition delay period which, in turn, results in a larger amount of fuel being injected into the cylinder prior to the start of ignition. During this period, a chain of processes leading to auto-ignition occurs, some of which are physical in nature while others are chemical.

For petroleum derived fuels, which are blends of hydrocarbons of various molecular weights, these physical and chemical processes occur at a rapid rate as fuel is injected. The relatively larger amount of fuel in the cylinder after an increased ignition delay receives a longer residence time in the cylinder and is better prepared for combustion. When auto-ignition does occur, the rate of pressure rise is much sharper than normal, resulting in engine "knock" and higher peak pressures. Thus, for petroleum derived fuels, a low cetane number is associated with longer ignition delay and rough combustion.

A longer ignition delay is expected from vegetable oils due to their generally higher viscosities and lower volatilities. Although a large amount of fuel accumulates in the cylinder during the ignition delay period, the physical and chemical processes that precede auto-ignition occur at a slower rate than exhibited by petroleum fuels. It is probable that this fuel would first burn at a relatively slow rate, increasing with time. If the faster portion of the combustion period occurs after top dead center (TDC), rapid pressure increases should be offset by the increasing volume of the combustion chamber. This reasoning implies that cetane numbers should be interpreted differently for VO and petroleum fuels.

A 200-hr durability test using the same test engine, a similar cycle, and a 50/50 fuel blend was also conducted by Baranescu and Lusco. The engine completed the test

¹¹ASTM D-975, "Test Method for Neutralization Number by Color Indicator Titration," *ASTM Annual Book of Standards* (American Society for Testing and Materials [ASTM], 1987).

with no performance problems. Daily starting was normal under the test cell environment and measurements of fuel system operation revealed no deterioration which would have required engine shutdown and inspection. The pressure drop across the fuel filters did not change throughout the test period. The lubricant's viscosity remained within normal limits during the test, and deterioration of the lubricant additives was not observed.

Upon completion of durability testing, the engine was dismantled and inspected. All nozzles were found to have heavy deposits on the combustion side of the tip and especially around the orifices. An energy dispersive x-ray spectrum was used to analyze the chemical composition of particles found in the deposits around the orifices. Iron and typical low-alloy steel elements were found in this analysis, indicating premature wear of the fuel system.

Over the test period, injection system wear was judged normal, fuel filter clogging was not observed, and the injection pump plunger looked normal. Sticky deposits were, however, found on the filter cartridge cap and on parts of the distributor body, pump body, delivery valve seat, injector body, and other areas that were exposed to stagnant fuel. In general, where there was no continuous fuel flow or, where clearances were small and fuel was in longer contact with metal surfaces, sticky deposits were found to have developed. This condition, which could become more severe over time, would be likely to impair fuel pump operation, increase internal friction, and adversely affect seals.

Heavy deposits were found on the ring belt area, the crown, the surface of the combustion chamber and on all pistons. In addition, heavy deposits were also found on the areas corresponding to the spray pattern geometries and the combustion chamber walls. This is proof that the fuel jets touched the wall and that liquid fuel impingement occurred under most operating conditions. Since vaporization of such a liquid jet is extremely slow when blends of sunflower oil are injected, most of the fuel burns on the chamber walls, leaving behind a heavy residue.

Combustion chamber fouling may lead to an increased rate of lubricating oil dilution. This event occurs when unburned fuel is allowed to pass by the piston rings and into the crankcase, which may happen when the cylinder liners are wetted with highly viscous vegetable oil or deposits are allowed to accumulate. Lubricating oil dilution is discussed in more detail when modifications to vegetable oils are covered in a later section.

Cold Weather Operation

Special problems may arise when burning vegetable oil in cold weather. After cooling from 145 °C to 104 °C, the vegetable oil's viscosity increases by an order of magnitude. Such a large change in viscosity can cause near-failure effects on injection system performance.

Baranescu and Lusco investigated this problem in the experiment mentioned previously. A significant difference in cloud point temperature was found for sunflower/diesel oil fuel blends. Subsequent fuel system and engine starting tests were run at temperatures at least 6 °C higher than the cloud point temperature for the respective blend in order to prevent fuel filter plugging. A dramatic increase in viscosity was found to occur for sunflower/diesel oil blends at the cloud point. For example, at the cloud point temperature for sunflower oil, the viscosity of sunflower oil is 250 cSt whereas the viscosity of a typical diesel oil is 10 cSt. This degree of increase in viscosity is likely to

affect flow through the fuel lines, reduce internal leakage necessary for injector pump lubrication, and possibly result in eventual injector system failure.

General cold weather requirements for satisfactory operation include the ability to crank the engine fast enough to start and the provision of adequate lubrication to internal bearing surfaces during starting and warmup. To facilitate these conditions, Detroit Diesel Allison (DDA)¹² recommends the use of auxiliary heat in the form of jacket water and oil pan heaters, hot-air space heaters applied to engine compartments, or some combination of these. Once warmed sufficiently, external weather conditions have little effect on the internal engine temperature.

Summary of Vegetable Oil Research

This chapter has discussed the use of vegetable oils as substitutes for conventional petroleum derived diesel fuels. Soybean, sunflower, safflower, and peanut oils were among the potential alternatives. In general, vegetable oils have proved workable as diesel fuel substitutes except in three problem areas: injector nozzle coking, combustion chamber fouling, and lubricating oil dilution. The rest of this report will deal with modification of vegetable oil to improve its combustion qualities with regard to these three criteria.

¹²Fuels and Lubricating Oils for Detroit Diesel Engines, Bulletin No. 270 (Detroit Diesel Allison, Detroit, MI, 1985).

3 FORMATION AND COMBUSTION OF VEGETABLE OIL MONOESTERS

Overview

Transesterification is a process that breaks down the large triglyceride molecules of a vegetable oil. The glyceride molecule joining the three fatty acid chains is stripped away and replaced by hydroxyl (OH) groups from an alcohol (normally methanol in this reaction), resulting in three shorter esters of the vegetable oil. The improved characteristics of an esterized vegetable oil make it a favorable candidate as an alternative fuel. By transesterifying the vegetable oil with an alcohol (methanol, ethanol, etc.), the viscosity of the vegetable oil decreases from being 11 to 17 times greater than that of diesel fuel to about 1.5 times greater. This decrease in viscosity substantially minimizes many of the complications associated with burning neat vegetable oil.

Summary of Past Experiments in Burning Vegetable Oil Monoesters

Goering and Daugherty¹³ compared 11 VO fuels to determine which vegetable oil methyl ester would be the most economical. They reported that a soybean oil methyl ester (MESO) is the superior choice because it is available in largest supply, is the least expensive, has the highest energy yield, and has a good yield per unit of growing area. Krawetz¹⁴ showed the similarity of properties between MESO and No. 2 diesel fuel (Table 1).

Table 1
Fuel Properties of MESO
Compared With No. 2 and Diesel Fuel*

Fuel Property	MESO Fuel	No. 2 Diesel
Pour point, °C	-1.1	-33.0
Cloud point, °C	1.1	-15.0
Flash point, °C	171.1	53
Gross heating value, kJ/kg	38,460	45,343
Viscosity at 40 °C, mm ² /sec	4.06	2.7
Cetane no.	50.7	51.4
Percent sulfur	0.04	0.01
Percent ash	0.01	0.01
Percent water and sediment	0.033	0.05
Carbon residue, %wt	0.10	0.01

*Source: A. A. Krawetz, "Properties of Soyoil Methyl Ester and No. 2 Diesel Fuel," unpublished report from Phoenix Chemical Laboratory (1983).

¹³C. E. Goering and M. J. Daugherty.

¹⁴A. A. Krawetz, "Properties of Soyoil Methyl Ester and No. 2 Diesel Fuel," unpublished report from Phoenix Chemical Laboratory (1983).

Evaluation of the combustion process gives a clear indication of the improved properties of the esterized vegetable oil compared to the neat vegetable oil. Zubik, et al.¹⁵ conducted an extensive study on the combustion process of esterized vegetable oil. Results showed that the level of premixed burning of the esterized oil was higher than that of diesel fuel. This finding was not attributed to longer ignition delay as it was for neat vegetable oil, but instead to the fact that the ester fuel seemed to burn faster. These researchers theorized that the faster burning was caused by poor air and fuel mixing and increased chemical reaction rates due to thermal decomposition of the ester during the ignition delay. Overall, the problems that result from burning esterized vegetable oils are minor compared with those from burning neat vegetable oil.

Engine performance using MESO was tested by Einfalt and Goering.¹⁶ The purpose of the tests was to determine the brake specific fuel consumption (BSFC), brake mean effective pressure (BMEP), and the overall performance level of a vegetable ester fuel. MESO was used as a fuel in an Allis-Chalmers 190 DI tractor engine. Over the duration of the test, BMEP stayed constant up through 300 hr and then began to decrease. Since this decrease was accompanied by a decline in mass fuel per injection and there was negligible change in the brake thermal efficiency, Einfalt and Goering attributed the drop in BMEP to a reduction in fuel delivery.

The engine performance of MESO compares well to that of diesel fuel. The cetane numbers of MESO and diesel fuel are very close, indicating that the MESO fuel should auto-ignite as well as diesel fuel. Thus, increased knock from the use of MESO fuel should not be a problem. However, since the cloud and pour points are much higher for MESO than for diesel fuel, some difficulty in starting the engine may be experienced in cold weather. The main performance differences between the two fuels can, for the most part, be attributed to the lower heating value of the soybean oil. This lower heating value requires an increased specific fuel consumption (BSFC) in order to produce the same amount of energy. This increase in fuel flow necessitates a higher fuel/air ratio for burning the vegetable oil compared with burning the diesel fuel.

Barsic and Humke¹⁷ suggested that a decrease in power output can be attributed to carbon accumulation on the combustion side of the nozzle tip. This accumulation may be caused by polymerization of triglycerides in the fuel. The difference in performance can be traced to the higher viscosity of the methyl soyate, which will result in less efficient combustion. Also, since the injection pump meters fuel on a volumetric basis, the denser soyate has an increased BSFC compared with diesel fuel.

In general, carbon deposits are heavier in an engine run on MESO than in one run on diesel fuel. One of the Einfalt-Goering tests showed that carbon accumulation for the soyate-fueled engine was slightly greater than the No. 2D diesel-fueled engine, with the only excessive accumulation of carbon deposits on the intake valves. Although it is not unusual for an engine run on diesel fuel to have carbon deposits on the intake valves at a level 50 percent greater than those on the exhaust valves, carbon accumulation on the intake valves in this case was 840 percent greater. Also, a dome of carbon was found on

¹⁵J. Zubik, S. C. Sorenson, and C. E. Goering, "Diesel Engine Combustion of Sunflower Oil Fuels," *Transactions of ASAE*, (1984), pp 1252-1262.

¹⁶J. Einfalt and C. E. Goering, "Methyl Soyate as a Fuel in a Diesel Tractor," *Transactions of ASAE* (1985), pp 70-71.

¹⁷N. J. Barsic and A. L. Humke, "Performance and Emissions Characteristics of a Naturally Aspirated Diesel Engine With Vegetable Oil Fuels (Part 2)," SAE Paper No. 810955 (SAE, 1982).

the tops of the exhaust valve guides. These domes were attributed to carbon transferred through the exhaust valve guides. Deposits on the piston were also slightly heavier, although not enough to cause great concern.

The major complication that limits long-term use of MESO as a fuel in a diesel engine is its effect on the lubricating oil. Two important parameters that MESO affects are the viscosity and the total base number (TBN). As lubricating oil dilution increases, the viscosity initially decreases. After a period of time and depletion of the oil's TBN reserve, however, polymerization of the oil begins to occur. This event results in an actual increase in viscosity. Tests intending to increase lubricating oil viscosity under simulated conditions found that viscosity does not increase unless a metal catalyst is present. Siekman, et al.¹⁸ performed a test to determine the time-dependent increase in lubricating oil viscosity for a 20 percent dilution of oil with MESO fuel. They proposed that copper is a catalyst essential to lube oil polymerization. In their attempt to induce lube oil degradation and thickening, they had included copper as the catalyst in a mixture of MESO and oil; thickening did occur in the mixture.

When comparing mixtures of 5, 10, and 20 percent MESO, it was found that the degree of dilution has a linear impact on the TBN. Further evaluation of results showed that, at 170 °C, the 10 percent dilution by MESO produces about the same change in alkaline reserve as does a 20 percent dilution at 150 °C. Summing the results, it appears that increases in either or both the temperature and the degree of dilution result in a drop in the TBN. The TBN reduction also became more significant at higher temperatures and with increasing time.

Use of the modified vegetable oil MESO has been reported to greatly reduce injector nozzle coking and combustion chamber fouling associated with neat vegetable oils as discussed above. The problem of lubricating oil dilution is discussed next in Chapter 4.

¹⁸R. W. Siekman, D. Blackman, G. H. Pischinger, and L. D. Carvalho, "The Influence of Lubricant Contamination by Methylesters of Plant Oils on Oxidation Stability and Life," *Proceedings of the First International Conference on Plant and Vegetable Oils as Fuels* (August 1982), pp 209-217.

4 LABORATORY EXPERIMENTS

Experience with lubricating oil dilution and subsequent gelation prompted a series of experiments at USA-CERL to induce and observe the effects of polymerization under laboratory conditions. The first experiment used methods outlined by Siekman, et al.¹⁹ to obtain gelation under high dilution levels (20 percent) and excessive temperatures. The second test attempted to identify the catalytic effects of common engine metals on polymerization at more reasonable dilution levels (2.5 and 5.0 percent) and temperatures.

Test 1: Thickening of 20 Percent (Vol) MESO/Lube Oil Solution

Purpose

This experiment was intended to determine the time-dependent increase in lubricating oil viscosity for a 20 percent dilution of oil with MESO fuel over a 1000-hr period. In addition, the feasibility of mechanical separation techniques was examined.

Experimental Procedure and Apparatus

Two 4000-mL Erlenmeyer flasks on thermocouple-controlled hotplate stirrers were used to simulate engine sump environments for two solutions: (1) 20 percent MESO and 40 wt lubricating oil and (2) a control containing 100 percent lubricating oil. The flasks were sealed with rubber stoppers, but vented through a glass tube. Arbitrarily chosen weights of about 0.97 g of aluminum foil, 3.7 g of copper foil, and 1.6 g of iron wire were suspended in each solution to permit possible catalytic interactions. The oil solution was kept at 93 °C. A Teflon-coated magnetic stirring bar agitated the mixture.

The solution was agitated continuously for 50 days, except for a 9-day shutdown period caused by a scheduling conflict. Thus, total actual running agitation time was 41 days. A standard dilution curve was run using an Perkin-Elmer infrared spectrophotometer in order to quantitatively determine the MESO/lube oil dilution. The differential absorption spectra were recorded for the fresh sample and control so that any change in concentration over the course of the test could be noted. Viscosity measurements were made at the same time daily using ASTM D-445²⁰ at 100 °F. The arithmetic mean of three readings was recorded for each sample.

At the end of the 50-day period, the experiment was terminated. A 450-g sample of the MESO/oil solution and a 225-g sample of the lube oil were set aside. A 360-mL sample of the remaining MESO/oil mixture was centrifuged at 3300 RPM for 2 hr. A 225-g sample of the centrifuged MESO/oil was taken and sediment from the bottoms of the centrifuge tubes was collected and saved. Differential infrared spectra were run for centrifuged MESO/oil vs. fresh lube oil and for uncentrifuged MESO/oil vs. fresh lube oil.

¹⁹R. W. Siekman, et al.

²⁰ASTM D-445, "Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)," *ASTM Annual Book of Standards* (1987).

Results

The freshly diluted MESO/oil solution had a viscosity of only 33.5 percent that of the pure lubricating oil. Viscosity versus time data for both the MESO/lube oil mixture and the pure lube oil are plotted in Figure 1. Linear regression was used to obtain a straight line fit to the pure lube oil data, as can be seen. The data for the MESO/lube oil mixture appeared to exhibit two distinct rates of viscosity increase, so a broken-line regression curve fit was applied. This yielded a breakpoint at 16 days and an overall R^2 value* of 0.94. The slopes of the line-fit segments are listed in Table 2.

The rate of viscosity increase for the MESO/lube oil mixture exceeded that for pure lube oil from the start. It appeared to experience an induction period during the first 16 days (period 1), increasing in viscosity at the rate of 0.37 cSt/day. After the sixteenth day, the rate of change increased to 1.99 cSt/day. This five-fold change may be related to depletion of additives in the oil, although TBN values were not determined on a daily basis. It is notable that the viscosity of the MESO/lube oil mixture never did increase to the level of the pure lubricating oil during the duration of the test. If the test had been continued longer and the viscosity rate of change had remained constant, it is estimated that the pure lube oil and MESO/lube oil lines would have intersected on day 67. This figure could be misleading, however, as gelatinous precipitates were already beginning to form in the flask by day 16. These precipitates would have a high potential for clogging oil passages in the engine.

It was also noted that the volatile components of the MESO/oil solution and pure oil would evaporate and recondense on the walls of the flask. In the MESO/oil solution, the condensate was clear during the induction period, but left green deposits (possibly copper oxide) afterwards. In addition, the MESO/oil solution became increasingly cloudy and discolored. A suspension of small particles was observed in the mixture as well as a black gummy sediment that accumulated in the bottom of the flask. When the flasks were emptied later, the MESO/oil flask had large amounts of this substance on the bottom and at the liquid/air interface along the flask walls.

Table 2
Rate of Viscosity Increase for 20 Percent
Dilution of MESO in Lubricating Oil

Treatment	Viscosity Increase
Pure lube oil	0.23 cSt/day
MESO/lube oil, period 1	0.37 cSt/day
MESO/lube oil, period 2	1.99 cSt/day

* R^2 = statistical "goodness of fit" for linear regression

MESO/LUBE OIL

Viscosity vs. Time

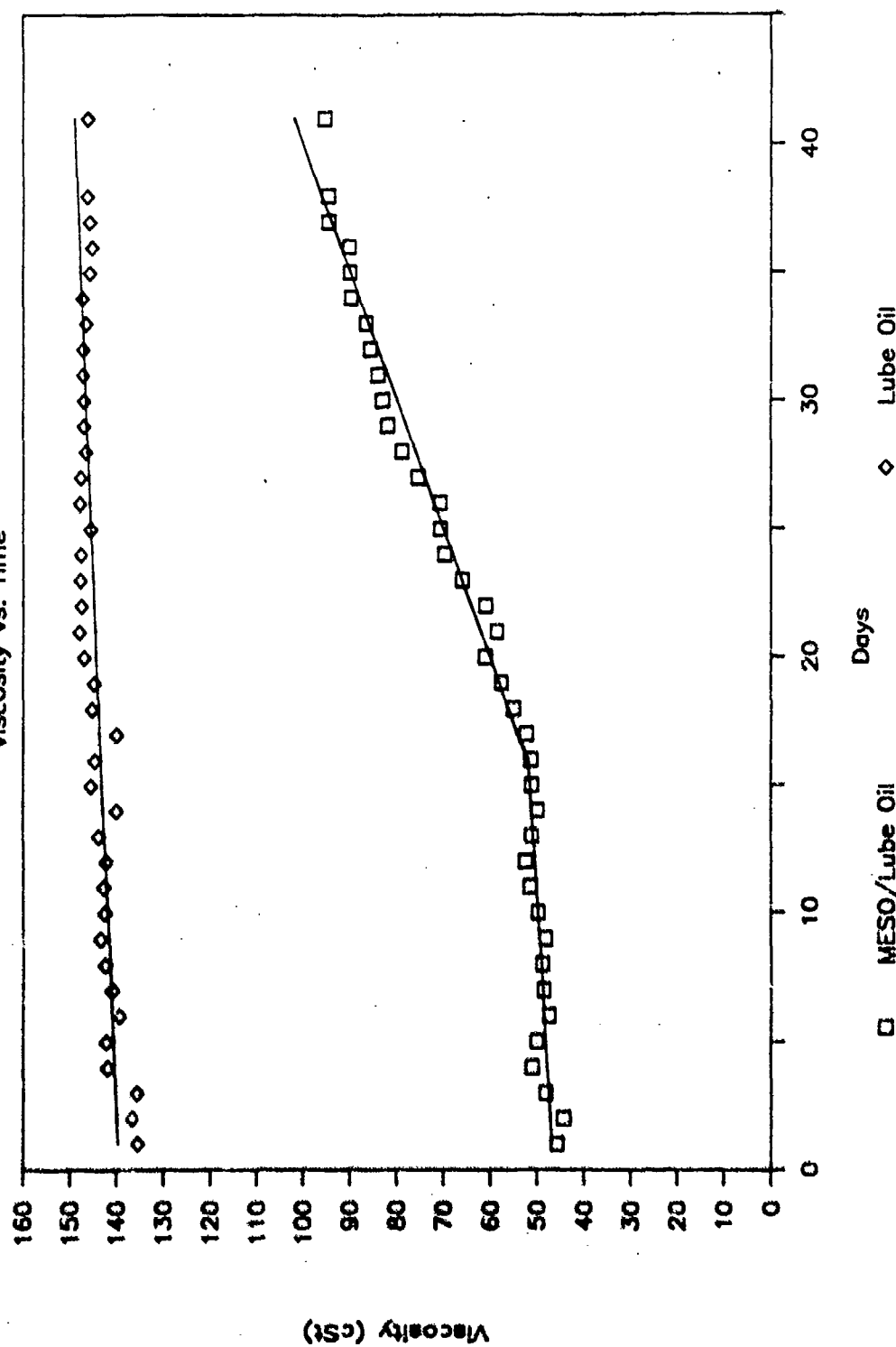


Figure 1. Viscosity of pure lubricating oil and 20 percent MESO/lubricating oil vs. time.

The MESO/oil also attacked the rubber stopper at the top of the flask. Initially, the stopper began to soften and swell. A ripple pattern began to form on the vapor side of the stopper, eventually showing drip marks--an indication that it had dripped into the MESO/oil solution. The Permatex used to seal the thermocouple into the Pyrex tube deteriorated badly. It was nearly liquid by the end of the experiment.

The pure lubricating oil exhibited none of the corrosive effects or discoloration evident in the MESO/oil mixture. The flask containing pure lube oil showed no residue after emptying.

The feasibility of mechanical separation of the polymerized MESO/oil was tested by spinning the mixture at 3300 RPM for 2 hr. This sample was compared with an uncentrifuged MESO/oil sample and the control sample of pure lubricating oil as follows:

1. The control sample of pure lubricating oil was clear and the same color as fresh lubricating oil. When filmed on the side of the glass sample jar, it was the same color as fresh oil.

2. The uncentrifuged MESO/oil sample was cloudy, dark, and brownish in color. This sample contained a suspension of many small particles and sediment formed on the bottom of the sample jar after a few hours. This sediment layer reached a thickness of approximately 1 cm after 2 weeks. When filmed on the glass side of the jar, this material contained a high density of fine particles that were almost black.

3. The centrifuged MESO/oil sample was also dark and of a brownish color, similar to the uncentrifuged MESO/oil sample. The centrifuged sample was not nearly as cloudy, however, as the uncentrifuged sample. When a film was made on the wall of the sample jar, it was much clearer than the uncentrifuged sample and had very little of the particulate matter present.

The sediment collected from the bottom of the centrifuge tubes was almost black and was very thick and gummy. This material retained the shape of the bottom of the centrifuge tubes for almost 1 hr after being placed into the sample jar, eventually congealing into a single mass. However, even after several weeks, lumps were present in this material, indicative of where individual pieces of the substance had fused together.

The infrared spectra of the uncentrifuged MESO/oil and the centrifuged MESO/oil vs. fresh lubricating oil indicated the presence of equivalent amounts of ester in each sample. This finding showed that the MESO was not being consumed in any appreciable amount by the polymerization process.

Discussion of Results

The viscosity increase observed during this experiment was of the nature and magnitude observed by researchers noted previously. It is notable, however, that the viscosity of the MESO/oil mixture never exceeded that of the undiluted lubricating oil. This finding suggests that, for oil change intervals on the order of hundreds of hours (common on smaller engines), polymerization is not likely to become a problem. It is on larger engines with oil change intervals in excess of 1000 hr that this polymerization could have serious consequences.

There was evidence of corrosion, which could conceivably cause more difficulty than polymerization. The three metals suspended in the solutions (copper, iron, and aluminum) are all common engine metals. Copper and aluminum alloys are commonly found

in bearings, whereas aluminum and steel are used as structural materials. The severe corrosion shown on the copper wire could prove highly detrimental to engine longevity by accelerating bearing wear; corrosion of steel surfaces could lead to early structural failure. In addition, the attack on the rubber stopper and permatex gasket material indicate that some common oil system components may not be compatible with lubricating oil that has been contaminated with MESO.

It is important to note that the level of fuel dilution (20 percent) used in this experiment was much higher than could reasonably be expected to occur in a well maintained diesel engine. It is common practice to change oil that shows more than a 5 percent dilution. The temperature at which this test was run (93 °C) is normal for some large engines, but may be high for others. For these reasons, it is important to assess the viscous behavior of MESO/oil mixtures at lower dilution levels and a slightly lower temperature. The next section describes an experiment conducted to examine the behavior of different combinations of metals and concentrations.

Test 2: Effects of MESO/Lube Oil Concentration and Metallic Catalysts on Viscosity, TBN, and TAN

The data from Test 1 yielded some interesting results with respect to rates of viscosity increase and corrosion of common engine metals. The test was designed to encourage gelation, however, and while certainly successful in this respect, the dilution concentration was unrealistic for many engines. In particular, dilution levels of 20 percent (vol) results in viscosity values much too low to provide adequate lubrication for an engine. In addition, while the possible catalytic effects of certain common engine metals have been discussed in the literature as noted in Chapter 2, there has been some disagreement over exactly which metals might be initiating these effects. In Test 1, copper, iron, and aluminum were all suspended together in the solution so as not to risk omitting an essential catalyst. Further work was necessary to evaluate various combinations of the above metals.

Purpose

Test 2 was designed to observe the time-dependent viscosity behavior of relatively low (2.5 and 5.0 percent) concentrations of MESO in lubricating oil. As an additional environmental factor, different combinations of copper, iron, and aluminum were suspended in the solution in a factorial design to study postulated catalytic effects.

Experimental Procedure and Apparatus

A total of forty-eight 225-g samples were tested, half at 2.5 percent (vol) concentration and half at 5.0 percent (vol). Each group of 24 samples was further subdivided into eight different metal combinations as shown in Table 3.

The sample bottles were heated in a constant temperature oil bath at 85 °C for 1176 hr (roughly 7 weeks). Aeration and mixing were provided by a filtered air bubbler system in each bottle. Viscosity measurements were obtained at the beginning of the test and weekly thereafter for the duration of the experiment. Differential infrared spectrophotometry, TBN, TAN, and trace metal analysis were performed for each sample at the beginning of the test and upon completion. Infrared spectrophotometry was done at USA-CERL, whereas tests for TBN, TAN, and trace metals were performed by the Army Fuels and Research Facility at Southwest Research Institute (SwRI).

Table 3
Metals Used in MESO/Lube Oil Treatments

Metal	Repetitions
Aluminum (Al)	3
Copper (Cu)	3
Iron (Fe)	3
Aluminum - Iron (AF)	3
Iron - Copper (FC)	3
Copper - Aluminum (CA)	3
Iron - Copper - Aluminum (FCA)	3
Control - no metals (CON)	3

Results

Viscosity measurements for both the 2.5 and 5.0 percent mixtures showed significantly different behaviors than those obtained for Test 1. The viscosity increases were very small over the duration of the test and certainly not comparable to the 50 cSt-plus range experienced previously. Initial values for the 2.5 and 5.0 percent mixtures were 112.93 and 100.86 cSt, respectively, whereas the final values were in the ranges of 114.93 to 118.37 and 101.05 to 104.05 cSt. Although there was a small increase, there was no apparent "breakpoint" or "induction period" and treatment increases were not much larger than measurement error involved for the viscometer.

More interesting results are apparent when the measured values for TBN and TAN are examined. In Figures 2 and 3, total base and acid number values are plotted for both the 2.5 and 5.0 percent concentrations of MESO in lubricating oil.

These values represent the mean for the three repetitions. On the right-hand side, data points over the IN label give the beginning values of TBN and TAN for the initial MESO/lube oil mixture. As can be seen from the plot, all samples had a significant decrease in TAN and TBN during the experiment. In the case of the control solution with no metals (CON), the TBN level decreased by 15 percent at the 5.0 percent concentration and by 12 percent for the 2.5 percent concentration.

The concentration of MESO in the lubricating oil was determined by infrared spectrophotometry. Absorption of light at a wavenumber of 1750 cm^{-1} for the full range of samples is plotted as corresponding dilution percentages in Figure 4. Both the 5.0 and 2.5 percent solutions showed a marked drop in dilution levels--possibly the result of chemical interaction with the lube oil. The different metals clearly affected the change in concentration, with the iron-copper-aluminum samples decreasing least. The higher concentration shows a greater range of dilutions as well. The metallic elements submerged in the samples had no noticeable corrosion; tests for trace metals showed no differences between samples.

Total Base Number

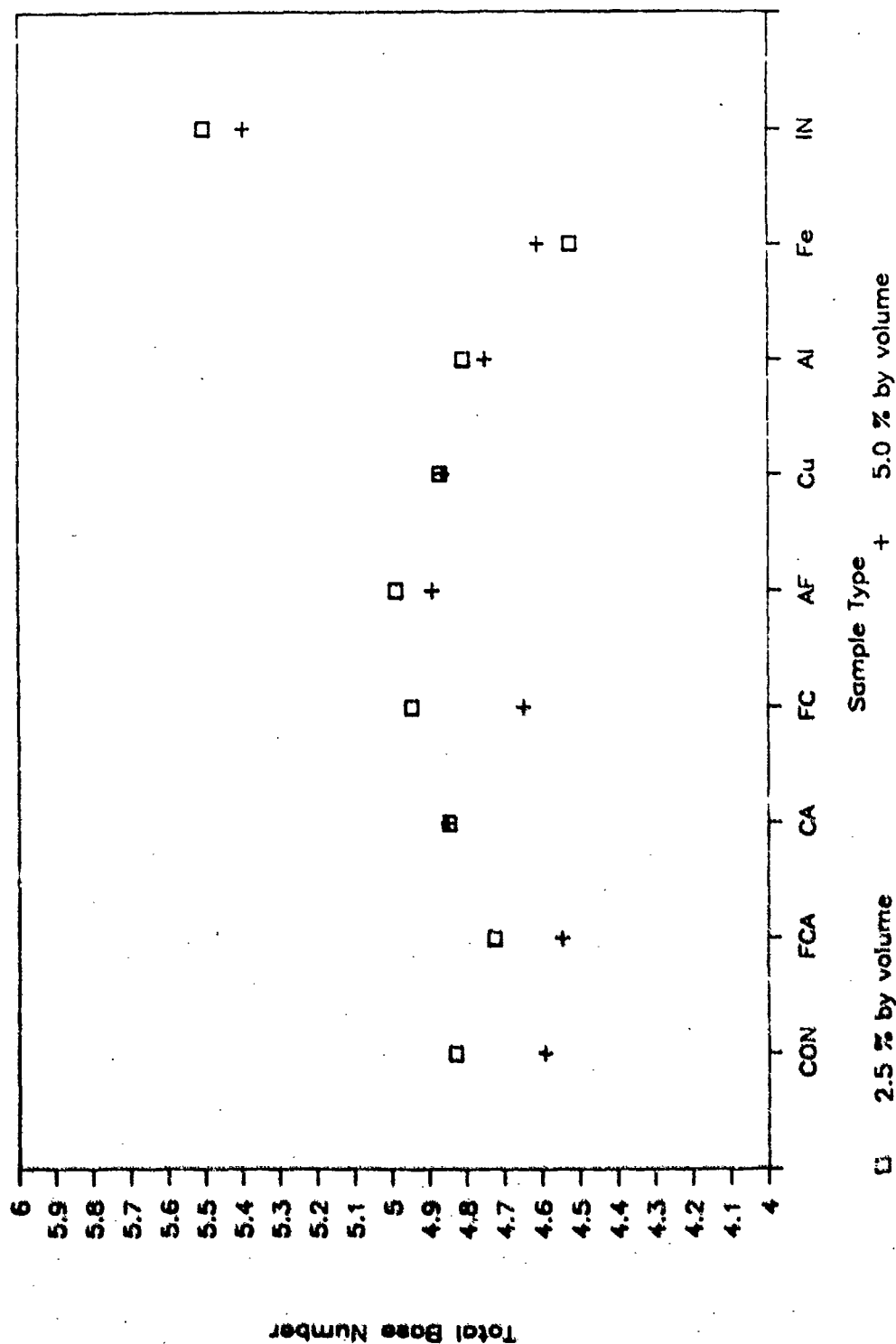


Figure 2. Total base number (TBN) of aged lubricating oil/MESO solutions with varying concentrations and metals.

Total Acid Number

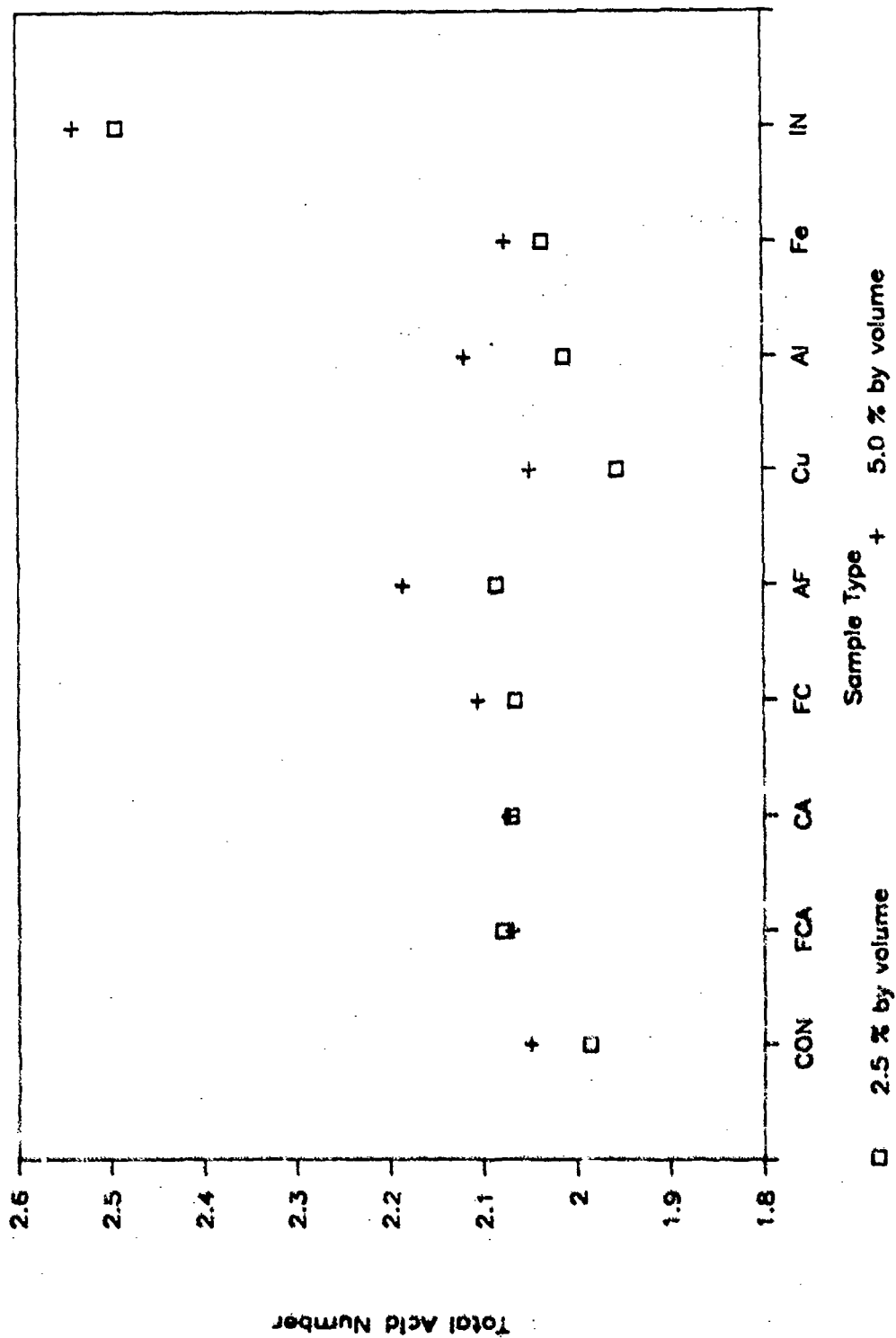


Figure 3. Total acid number (TAN) of aged lubricating oil/MESO solutions with varying concentrations and metals.

MESO/Lube Oil Dilution

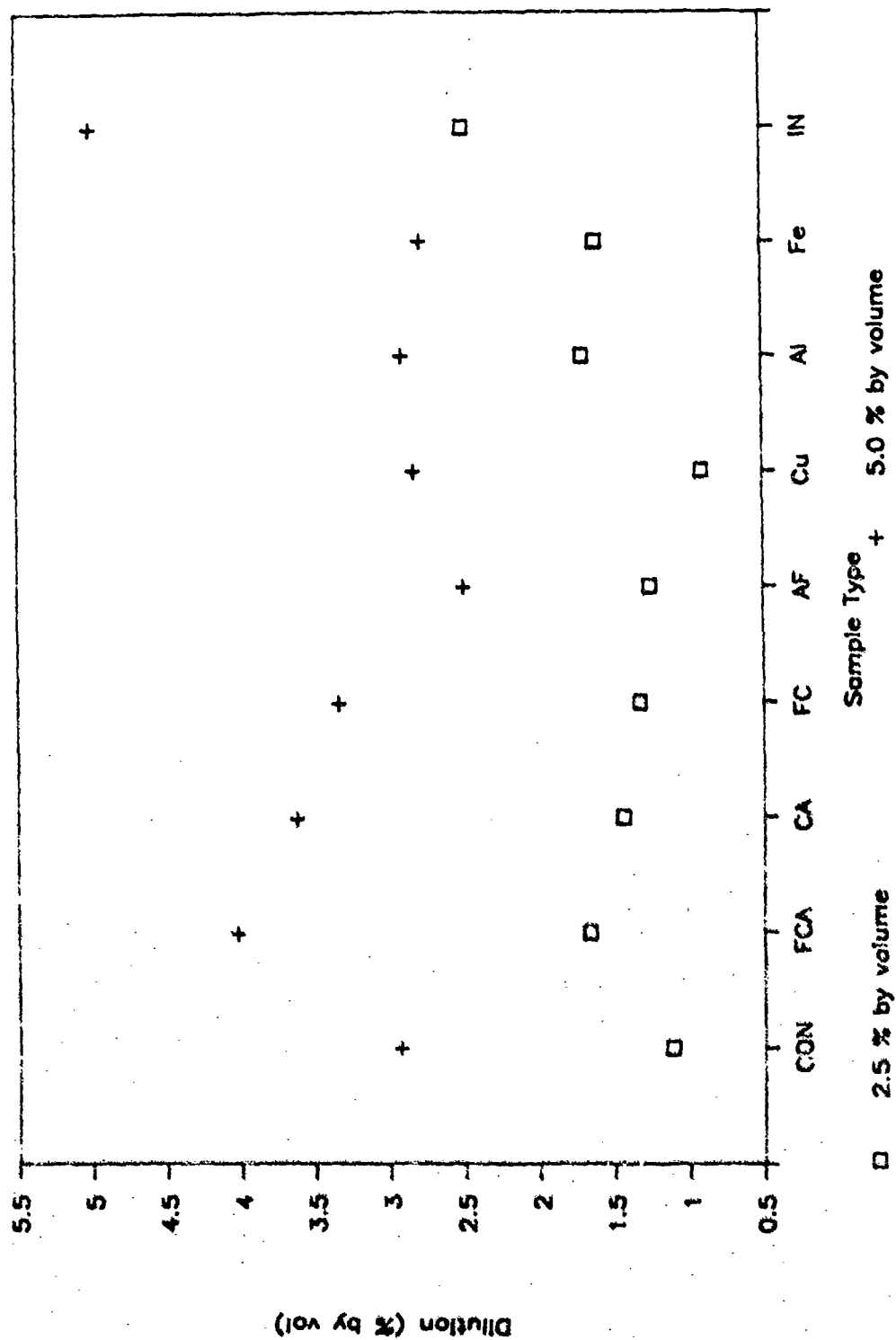


Figure 4. Dilution of aged lubricating oil by MESO with varying initial concentrations and metals.

Discussion of Results

The single most interesting result of this experiment is that no significant thickening of the mixtures occurred, unlike the 20 percent dilution used in Test 1. The TBN level did drop, although not to the point where it would have been necessary to change the oil. It has been suggested that polymerization occurs only after an oil's TBN reserve is exhausted. This theory is supported in part by the failure to thicken at lower dilution levels. Since a 20 percent dilution is not a practical level for continued operation, it is reasonable to predict that a high rate of dilution will cause excessive thinning of the lube oil prior to dangerous polymerization. Although no TBN measurements were obtained for Test 1, the initial 20 percent dilution level would have lowered the TBN at the beginning of the test more than the 5.0 or 2.5 percent levels would. As the test progressed, the dilution levels dropped in proportion to this initial level, meaning that mixtures beginning with a high dilution level would have their alkaline reserves depleted much earlier.

It was not possible to measure the different metals' effects on thickening. They did, however, appear to have some effect on TBN changes. The concentration of MESO was also noticeably affected by the type of metal in solution, indicating that different metals may have catalytic or inhibiting effects on chemical interactions within the solutions. Further work with similar metals at higher concentrations would be necessary to draw any further conclusions. If dilution levels are kept below permissible limits (2.5 to 5.0 percent), it appears unlikely that serious short-term corrosion problems will occur.

The two laboratory tests reported above showed that lubricating oil thickening can be caused under laboratory conditions, but only at high dilutions. When a 20 percent dilution was used, not only did thickening occur as predicted, but substantial corrosion was noted after the induction period. At more reasonable dilution levels of 2.5 and 5.0 percent, however, few significant changes were observed. The oil did not thicken noticeably and the metals present as catalysts did not present overwhelming evidence of catalytic effect. It appears likely that proper care and attention to the level of lubricating oil dilution would permit safe operation of an engine with MESO for periods under 1000 hr.

5 FIELD TEST OF MESO FUEL

To verify the reported satisfactory operation of diesel engines on a monoester fuel, a field evaluation was arranged with the USACE. Army Corps of Engineers St. Louis District. The test fuel was the same MESO formulation used in the laboratory experiments described in Chapter 4. The test engine was a diesel-powered emergency generator located inside the Lake Shelbyville Dam in midstate Illinois.

The engine was a DDA two-stroke, naturally aspirated, four-cylinder model 4-71 rated at 60 kW/1800 RPM. This engine typically is run for 1 week. An electrical load is provided using a resistance heater on a monthly basis. The lubricating oil has been changed every 135 hr of operation (about once per year). The engine had 1100 hr of operation on the tachometer-mounted hour meter at the start of the test. The entire generator set and fuel system are located within a heated room inside the dam, which is kept at 15.6 °C during winter.

Purpose

The main purpose of this test was to verify the feasibility of MESO combustion in a diesel engine under controlled field conditions. A secondary purpose was to monitor the rate and effects of lubricating oil contamination for an engine of this type. The lubricating oil was analyzed to detect changes in viscosity, dilution, TBN, and TAN.

Apparatus

A separate fuel tank was used to hold the MESO fuel. It was piped to the existing fuel system as shown in Figure 5. The three-way valve on the supply piping determined the fuel source for the engine, while an identical valve on the return side diverted excess fuel from the engine into the appropriate tank. In addition, gate valves served to divert the return fuel to either the MESO tank or a waste container. To switch from diesel oil to MESO, the supply side three-way valve was aligned to introduce MESO. Next, with the cut-off valve closed and drain valve open to divert return fuel to waste, the return side three-way valve was aligned to send fuel through the MESO return line. Once a steady stream of MESO began flowing from the waste tube (established by odor), the cut-off valve was opened and the drain valve closed. The resulting closed-loop system duplicated the diesel No. 2D system. To return to diesel No. 2D fuel operation, the process was reversed.

The engine fuel system filters the fuel just prior to the engine fuel pump and again just prior to the unit injectors. These filters were kept in place for the duration of the test, with periodic inspections for fouling. They were changed at the end of the test.

A primary concern in this test was to determine if the MESO fuel would in fact reduce the rapid injector and combustion chamber fouling reported for neat vegetable oil. Although the engine was not completely disassembled, several components were examined through inspection ports on the engine airbox. The unique configuration of the two-stroke engine allowed viewing of the combustion chamber through scavenging ports in the cylinder liner. Use of a flashlight and inspection mirror provided for observation of the intake airbox, piston bowls, injector tips, cylinder walls, piston rings, and valves. Ring status was checked by pressing lightly on the rings with a screwdriver to detect sticking or the presence of deposits behind the rings.

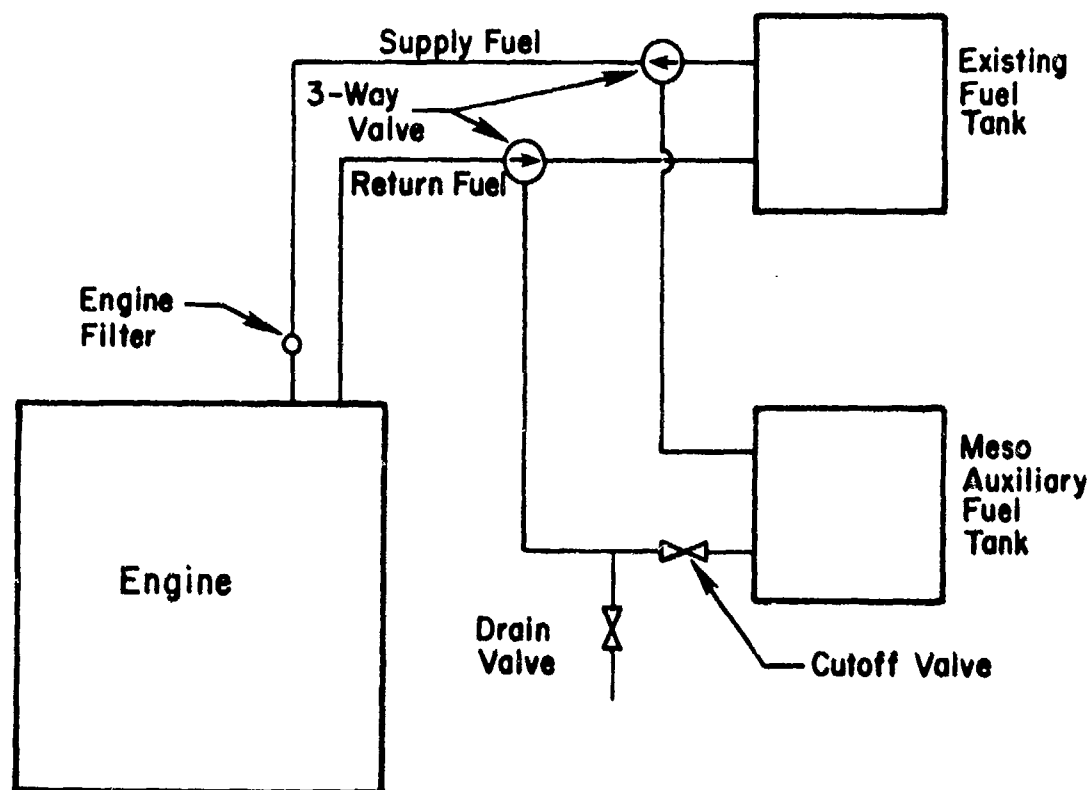


Figure 5. MESO fuel system.

The DDA 4-71 uses a wet sump lubricating oil system with a wire mesh strainer for filtration. Oil samples from the sump were obtained by means of a drain tube with a valve on the end. Samples were obtained from the drain tube after allowing sufficient flow to clear the dead volume area from the tube.

An electrical load was provided by an air-cooled resistive load bank capable of switching in resistor banks by increments of 5, 10, and 13.3 kW. The target load for the test was 80 to 85 percent of rated full load, which was provided by switching in three 13.3-kW banks for 49.9 kW (83 percent).

Data Collection and Procedures

MESO Fuel Properties

Table 4 lists fuel properties for the MESO as reported by Clark, et al.²¹ A total of 625 L of fuel was purchased for the test.

²¹S. J. Clark, L. Wagner, M. D. Schrock, and P. G. Piennaar, "Methyl and Ethyl Soybean Esters as Renewable Fuels for Diesel Engines," *JAOCS*, Vol 61, No. 10 (1984), pp 1634.

Table 4
Fuel Properties of MESO and No. 2 Diesel Fuel*

Test Property	Diesel ASTM Test**	Fuel No. 2	MESO
Viscosity at 40 °C (cSt)	D-445	2.39	4.08
Specific gravity (at 15.6 °C)	-	0.847	0.884
Higher heating value (MJ/kg)	D-240	45.2	38.8
Cetane no.	D-613	45.8	46.2
Cetane index	D-976	46.0	Off Scale
Distillation (90% - °C)	D-86	296	342
Pour point (°C)	D-97	-23	-1
Cloud point (°C)	D-2500	-19	2
Flash point (°C)	D-93	78	141
H ₂ O and sediment (% vol)	D1796	trace	trace
Sulfur (% mass)	D-129	0.25	0.01
Corrosion	D-130	1-a	1-a
Ash (% mass)	D-482	0.025	<0.01
Gum no. (cg/L)	D-2274	8.0	16,400
Color (ASTM color code)	D-2274	L3.0	L.15
Color (ASTM color code)	D-1500	L2.0	L2.0

*Source: S. J. Clark, et al.. "Methyl and Ethyl Soybean Esters as Renewable Fuels for Diesel Engines," JAOCS, Vol 61, No. 10 (1984). Used with permission.

**ASTM Annual Book of Standards (1987).

Engine Operation and Starting Ability

The engine was started by the area office electrician using normal diesel fuel, and the electrical load gradually increased to 49.9 kW over 15 min. After 10 min of operation at load, the engine was switched over to MESO in the way described above. The engine was run approximately 6 hr/day, as the availability of onsite staff permitted. After the first day, the engine was started on neat MESO. The actual running schedule is shown in Table 5.

Table 5

Engine Running Schedule for Lake Shelbyville Diesel Engine Test

Date	Time	Event
25 Feb 86	1210	Started engine on No. 2 diesel fuel
	1240	Switched to MESO fuel
	1520	Shut down engine
26 Feb 86	1125	Started engine on MESO
	1500	Shut down engine
03 Mar 86	0310	Started engine
	1530	Shut down engine
06 Mar 86	0806	Started engine
	1530	Shut down engine
07 Mar 86	0815	Started engine
	1530	Shut down engine
10 Mar 86	0810	Started engine
	1010	Switched to No. 2 diesel
	1045	Shut down engine on No. 2 diesel

Makeup fuel was pumped by hand from drums into the 380-L MESO tank. Lubricating oil was changed prior to test startup and after the test ended. Lubricating oil was checked prior to each morning's start and makeup oil added as needed. Samples were obtained at approximately lunchtime and just before the engine was shut down for the day. The cylinders were inspected through the airbox inspection covers prior to the start of the test, after the first day of operation, and upon completion of the test. The engine fuel filters and lubricating oil strainer were inspected at the beginning and end of the test.

Lubricating Oil Condition

Lubricating oil tests were performed by the Army Fuels and Lubricants Research Facility at SwRI. These tests are listed in Table 6.

Results

Engine Operation and Starting Ability

There was no readily apparent difference between operation on No. 2 diesel fuel and MESO. The engine was switched to MESO without a change in audible tone or RPM. Exhaust smoke was somewhat clearer on MESO than with the No. 2D diesel. There was a noticeable, but not objectional, odor with MESO. The engine started readily on the MESO, even after a 5-day shutdown.

Table 6

Type and Periodicity of Tests Performed at Lake Shelbyville

Parameter	Test	Frequency
Viscosity	ASTM D-446-74	Twice Daily
Total acid number (TAN)	ASTM D-664	"
Total base number (TBN)	ASTM D-664	"
Fuel dilution	Infrared spec.	"

*ASTM Annual Book of Standards (1987).

Lubricating Oil

Anticipated problems included fuel oil dilution, polymerization, and TBN degradation. Figure 6 shows the infrared absorption of lube oil samples drawn from the engine, which is related to the degree of dilution as discussed earlier. A linear regression technique was used to fit a line to the absorption data points. The engine had a relatively high rate of dilution (0.067 percent/hr), with a concomitant viscosity decrease (0.59 cSt/hr, measured at 37.78 °C (100 °F)). The engine lubricating oil strainer was inspected before test start, after 3 hr of running, and again after test completion. There was no discernible residue or particulate matter in the strainer. It is apparent that, for this particular engine, the oil would need to be changed due to dilution long before polymerization becomes a problem.

Engine Deposits

The following conditions were observed prior to the start of the test:

- Cylinder liners - Clean, hone marks visible, light scoring on No. 2 cylinder.
- Piston heads - 50 to 80 percent covered with white, flaky deposits.
- Rings - All rings were free; lands had light, gummy deposits. Gumming on no. 4 was heavier.
- Intake valves - Medium to light deposits.
- Exhaust valves - Medium deposits heavier on no. 4.
- Injectors - Even, light-gray deposits on tips.
- Orifices - Unobstructed; no cone formation.

Shelbyville Diesel Engine Test

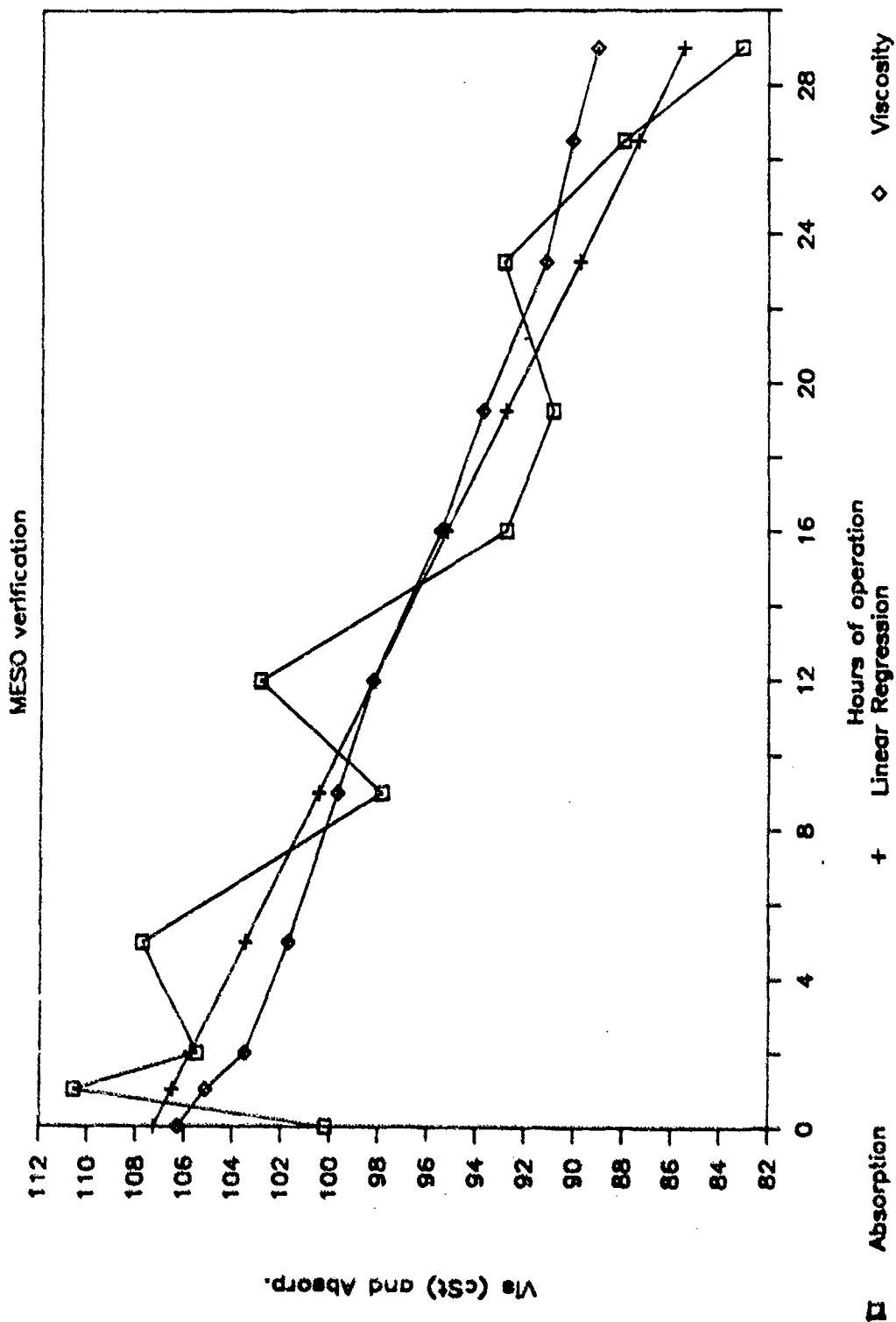


Figure 6. Viscosity and infrared absorption vs. time for the Lake Shelbyville diesel engine test.

After 3 hr on MESO, the cylinders were inspected to ensure that no catastrophic cylinder or injector fouling was occurring. No change was noted.

Cylinders were inspected upon completion of the test:

- Cylinder liners - No change.
- Piston heads - No change.
- Rings and skirt - Pistons 1 and 2 showed additional black, gummy carbonaceous deposits on the lands. Amber lacquer extended down skirt. Rings free.
- Intake valves - No change.
- Exhaust valves - Medium deposits, appeared darker and slightly wet.
- Injectors - No further buildup.

Discussion of Results

Despite the short duration and field conditions of this verification test, none of the results disagreed with engine tests reported in the fairly large body of current literature. The most notable and catastrophic consequences of burning straight vegetable oil-combustion chamber fouling and nozzle coking--were not evident during this test. Dilution of the lubricating oil with fuel oil remains a major problem, which would probably require redesign of the fuel injection system to solve. Emergency use of MESO in the future would require careful monitoring of engine oil viscosity to prevent excessive loss of viscosity or polymerization. The results of this test support the studies reviewed earlier in concluding that MESO can be a satisfactory substitute for conventional petroleum diesel fuels in diesel engines, given proper care and precautions.

6 CONCLUSIONS AND RECOMMENDATIONS

This study has assessed the feasibility of using vegetable oils and their derivatives as an alternative to petroleum fuels in diesel engines supporting Civil Works. After a literature search to identify promising candidate VO fuels, laboratory and field testing were conducted to study engine performance and any detrimental effects of using the fuel substitutes.

The literature search revealed that pure ("neat") vegetable oil is not suitable for use as an alternative diesel fuel for high-speed, direct-injection engines. The combined problems of high viscosity, injector nozzle coking, combustion chamber fouling, lubricating oil dilution, and high cloud point present difficult and economically unattractive hurdles to use. For the few remaining indirect-injection engines within the Civil Works inventory, however, pure vegetable oil could be a reasonable choice. Most engines in this category are now installed in the Caterpillar bulldozers used for revetment work along the Mississippi river. As noted in this report, the Caterpillar 3306 PC/TC has been operated with no apparent durability problems. If vegetable oil were used in cold weather, fuel tanks would need to be equipped with heaters to keep the fuel above its cloud point.

Based on the available literature, laboratory tests performed at USA-CERL, and a limited field test, a methyl ester of soybean oil (MESO) will perform reasonably well as a diesel fuel if petroleum-based No. 2D fuel is unavailable or prohibitively priced. Certain precautions need to be observed during engine operations, however. In addition, long-term durability has not been established.

If MESO is selected as an alternative fuel, it is recommended that an SAE 40 single-grade oil be used to minimize the thinning effect of lubricating oil dilution, and that it be changed if the viscosity decreases by more than 15 percent or increases by more than 40 percent.²² In no case should engine manufacturer's oil change interval recommendations be exceeded. (It is also important to note that the use of an unapproved fuel may void a manufacturer's warranty.) The engine oil's TBN should be monitored. Depending on the test used, the oil should be changed if it falls below 1.0 for ASTM test D-664²³ or below 2.0 for D-2896.²⁴

To ensure proper engine operation, exhaust and intake valves should be inspected regularly (every 50 hr) for signs of carbon accumulation. Any excessive deposits should be removed. Fuel injector orifices should be inspected as well. As with any diesel fuel, it is wise to operate in the 80 to 90 percent of full load regime when possible, avoiding long periods at idle or partial load. If temperatures below 2 °C are expected, fuel tank heaters should be installed.

There is potential for using vegetable oil as a diesel fuel alternative, but only with the exercise of due care by personnel operating the equipment. For indirect-injection engines, some vegetable oils may be used in neat form. Indirect injection engines can operate on MESO if close attention is paid to the lubricating oil condition. Many

²²"Fuels and Lubricating Oils for Detroit Diesel Engines," *Bulletin No. 270* (Detroit Diesel Allison, September 1985).

²³ASTM D-664, "Test Methods for Thickness of Diffusion Coating," *ASTM Annual Book of Standards* (1987).

²⁴ASTM D-2896, "Test Method for Total Base Number of Petroleum Products by Potentiometer Perchloric Acid Titration," *ASTM Annual Book of Standards* (1987).

research areas on this subject remain to be explored, including MESO-compatible lubricating oils, fuel injectors designed for more viscous fuels, and piston ring configurations designed to minimize heavy fuel blow-by. VO fuels represent a renewable resource that will be available when and if the Corps of Engineers requires an emergency fuel for limited applications.

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